AGE AND STRATIGRAPHY OF THE SWEETWATER AND OTAY FORMATIONS, SAN DIEGO COUNTY, CALIFORNIA

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ABSTRACT

The discovery of both late Eocene and late Oligocene mammal fossils in strata that have generally been assigned to the Sweetwater Formation necessitates a revision of the age and stratigraphic relationships of the Sweetwater and Otay formations. The Sweetwater Formation is here redefined to contain only the distinctive "red mudstone unit" and is entirely of late Eocene age (latest Uintan and/or Duchesnean land mammal "age", ca. 37-42 Ma). The "conglomerate" and "gritstone" units, assigned to the Sweetwater Formation by most recent authors, are shown to be of late Oligocene age and are here included in a redefined Otay Formation. The Otay Formation disconformably overlies the Sweetwater Formation and is subdivided into three informal members: a basal "conglomerate member", a middle "gritstone member", and an upper, bentonite-rich "sandstone-mudstone member." The uppermost two members of the Otay Formation contain vertebrate fossils correlative with the early portion of the Arikareean North American land-mammal "age", ca. 29 Ma. Deposition of the basal conglomerate member of the Otay Formation may have begun in response to the dramatic drop in global sea-level that occurred about 30 Ma.

INTRODUCTION

From 1986 to the present, paleontological salvage operations conducted by PaleoServices, Inc. during grading operations in the southwestern portion of San Diego County have resulted in the collection of age-diagnostic vertebrate fossils from three of the four lithostratigraphic units discussed in this report. These four units are referable to the Sweetwater and Otay formations of Artim and Pinckney (1973). Before the discovery of vertebrate fossils and the increased attention paid to field work, the age, lithologic content, and stratigraphic nomenclature of these units was unsettled.

The goals of this paper are to: (1) describe the lithology and distribution of the four lithostratigraphic units that make up the Sweetwater and Otay formations; (2) establish the superpositional relationships of these units; (3) establish the geologic age of these units by means of the vertebrate fossils recovered from each; and (4) propose a stratigraphic nomenclature that reflects the actual sequence of depositional events that took place in southwestern San Diego County during the late Paleogene.

GEOLOGICAL SETTING

The study area (Fig. 1) is located in the coastal plain and western foothills of the Peninsular Ranges province of southern California (Gastil et al., 1975). Crystalline basement rocks along the western side of the Peninsular Ranges are dominated by a series of pre-batholithic metasedimentary and andesitic metavolcanic rocks known as the Santiago Peak Volcanics (Larsen, 1948). Fossil evidence (Fife et al., 1967) and radiometric evidence (Herzig and Kimbrough, 1991) indicate a late Jurassic and early Cretaceous age for this complex unit. The Santiago Peak Volcanics were intruded by a variety of granitic to gabbroic plutons of the Southern California batholith during the early to mid-Cretaceous (Krummenacher et al., 1975). These plutonic rocks form the bulk of the Peninsular Ranges to the east of the study area.

The coastal plain of San Diego County and northwestern Baja California is underlain by a thick sequence of relatively undisturbed Upper Cretaceous, Eocene, Oligocene, Miocene, Pliocene, and Pleistocene sedimentary rocks (e.g., Hertlein and Grant, 1954; Minch, 1967; Kennedy and Moore, 1971; Howell and Link, 1979; Deméré, 1983). In places, outliers of the crystalline basement protrude through this Tertiary sedimentary sequence to form resistant isolated hills (Peterson and Nordstrom, 1970). Geomorphically, the coastal plain is characterized by a "stair-step" series of elevated Pleistocene marine terraces (Kern, 1977) that have been dissected by west-flowing rivers that drain the Peninsular Ranges to the east. The La Nacion and Rose Canyon fault systems (Artim and Pinckney, 1973; Kennedy, 1975) represent the major structural elements of the coastal plain. The La Nacion system consists of a series of normal faults with a general down-to-the-west sense of separation, while the Rose Canyon system is thought to have had a considerable amount of strike-slip movement. Urbanization, vegetation, and the Pleistocene terrace veneers combine to limit bedrock outcrops primarily to artificial exposures such as roadcuts and construction projects.

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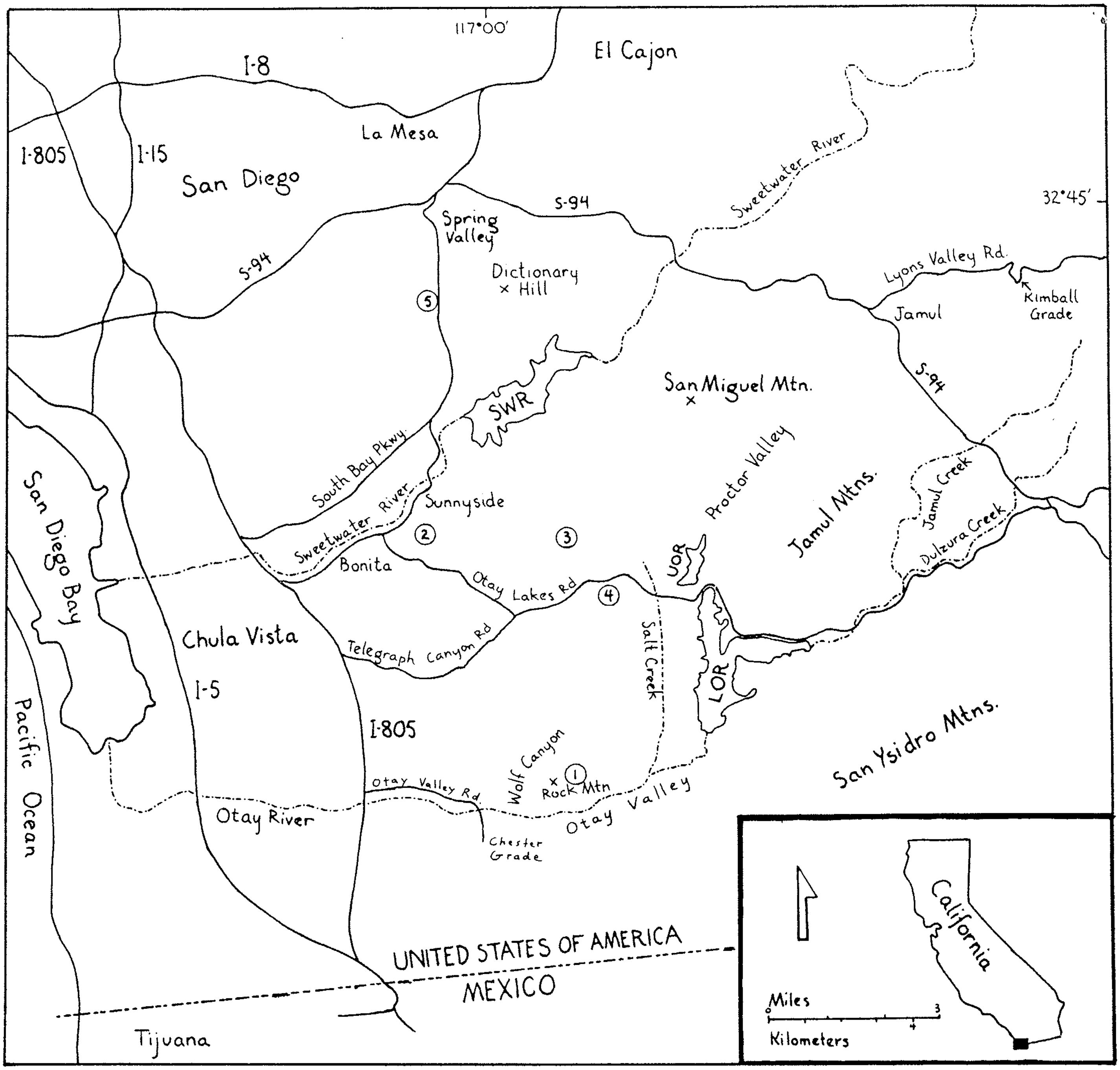

Figure 1. Map showing location of geographic features and measured sections (1-5) discussed in text. SWR = Sweetwater Reservoir; UOR = Upper Otay Reservoir; LOR = Lower Otay Reservoir.

PRELIMINARY NOTIONS

Before discussing the age and stratigraphy of the Sweetwater and Otay formations, and to better communicate what we mean by these names and why, it is first necessary to outline our view of the goals of stratigraphic nomenclature, and then distinguish between the terms "facies" and "lithostratigraphic unit."

In our view, the stratigraphic nomenclature of a region should reflect the depositional history of that region. When new fossil, radiometric, or stratigraphic evidence shows that an existing nomenclature is inconsistent with the depositional history of an area, it should be revised. For example, the North American Stratigraphic Code states (1983, p. 855): "Revision [of a lithostratigraphic unit] is justifiable if a minor change in boundary or content will make a unit more natural and useful." We believe that a revision of the lithologic content of the Sweetwater and Otay formations will indeed make these units more "natural" and useful. In particular, we will propose that the boundary between these two formations be redefined in order to correspond with a major disconformity that we recognize within rocks that most previous workers have mapped as the Sweetwater Formation.

Finally, we must clarify the difference between the terms "lithostratigraphic unit" and "facies" (or "lithofacies"). By a lithostratigraphic unit, we mean any sedimentary body of a given stratigraphic rank, of distinctive age and/or lithology relative to other such bodies, that also bears a consistent superpositional relationship to other such bodies of the same stratigraphic rank (cf. North American Commission on Stratigraphic Nomenclature, 1983, p. 855). Formal lithostratigraphic units are given proper names and ranked as groups, formations, and members. In contrast, the term "facies" or "lithofacies" merely designates a particular lithology that can occur repeatedly in one or more lithostratigraphic units of very different ages. This problem has been particularly acute in the case of the Sweetwater and Otay formations, where facies of similar lithology have led previous workers to assume them to be the same age, and so have assigned them to the same lithostratigraphic unit.

In this paper we recognize four different post-Mission Valley Formation (Kennedy and Moore, 1971), pre-San Diego Formation (see review in Deméré, 1983) lithostratigraphic units in southwestern San Diego County. The oldest of these is the "red mudstone unit", which is here referred exclusively to the redefined Sweetwater Formation. The three youngest lithostratigraphic units form the redefined Otay Formation of our usage. From stratigraphically lowest to highest these are the "conglomerate", "gritstone", and "sandstone-mudstone" units, and are regarded by us as informal members of the Otay Formation. When viewed together these three "members" appear to represent related parts of a previously unrecognized alluvial fan/braided river depositional system. This paper is intended as a preliminary but provocative report of ongoing field work,that we hope will be fruitful in stimulating new research on several remaining problems.

PREVIOUS WORK

The Sweetwater and Otay formations of southwestern San Diego County were named by Artim and Pinckney (1973) for a series of distinctive terrestrial sedimentary rocks that had traditionally been mapped as part of the marine San Diego Formation of late Pliocene age (e.g., Hertlein and Grant, 1954; Cleveland, 1960; Kennedy and Moore, 1971). Unfortunately, Artim and Pinckney (1973) failed to designate type sections or type areas for either formation. This omission has made it difficult for subsequent workers to understand what Artim and Pinckney actually meant by the terms "Sweetwater Formation" and "Otay Formation." To illustrate the extent of this confusion, Figure 2 shows five similar schematic diagrams of the stratigraphic relationships among the various lithostratigraphic units of the Sweetwater and Otay formations. Superimposed on the diagrams are five different versions of stratigraphic nomenclature that have been applied to these units since 1973.

Artim and Pinckney (1973, p.1076-1077) described the Sweetwater and Otay formations as follows:

"The San Diego Formation east of La Nacion fault is underlain by two distinctly different, previously unrecognized formations. These are the Miocene Otay Formation and the Eocene Sweetwater Formation. The Otay Formation consists predominantly of 35 to 50 m of white, volcanically derived tuffaceous fine sandstone with thin bentonitic interbeds, marked by a basal breccia conglomerate unit. The Sweetwater Formation consists of a lower gritty sandstone member overlain by a 35 m-thick red claystone member."

The important points in these original descriptions are that the Sweetwater Formation is defined as having an upper "red claystone member" and that the Otay Formation is defined as consisting of tuffaceous and bentonitic sandstones with a basal "breccia conglomerate unit." Unfortunately, Artim and Pinckney's (1973) lithological characterizations of the Sweetwater and Otay formations are contradicted in part by the distribution of these units as plotted on their geologic map (Artim and Pinckney, 1973, Fig. 3). That is, Artim and Pinckney say that the Otay Formation is marked by a basal breccia conglomerate (presumably, the "conglomerate" and "gritstone" members of our usage), and mention no conglomerate at all in the Sweetwater Formation, yet the extensive conglomerate deposits that crop out in the Proctor Valley and Otay Lakes areas appear on their map as Sweetwater Formation, not Otay. This contradiction may have led later workers to assume that all of these coarse-grained strata should be assigned to the Sweetwater Formation rather than the Otay (see below).

Apparently, Artim and Pinckney (1973) assigned an Eocene age to the Sweetwater Formation on the basis of superposition, noting that it occurred above a "known Eocene formation" (although they did not state the name of this formation). The Otay Formation was suggested to be correlative with the Miocene Rosarito Beach Formation of northwestern Baja California, Mexico, presumably on the basis of lithological similarity.

As originally described by Minch (1967) and updated by Minch et al. (1984), the Rosarito Beach Formation consists of seven members including from oldest to youngest the La Mision and Los Indios members near Ensenada, and the Mira al Mar, Costa Azul, Amado Nervo, Las Glorias, and Los Buenos members near Rosarito. These members consist of basaltic flows (La Mision and Costa Azul members), tuffaceous sandstones (Los Indios

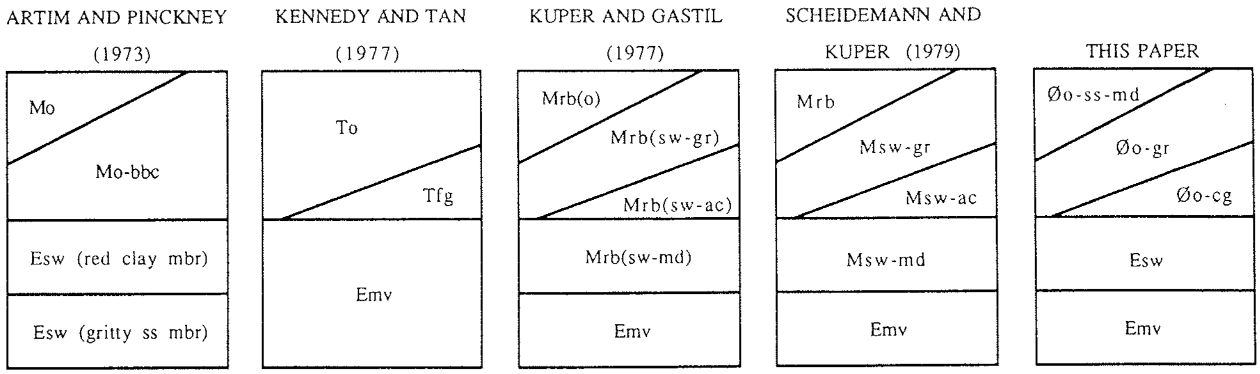

Figure 2. Summary of the history of stratigraphic nomenclature for the Sweetwater and Otay formations in southwestern San Diego County. Abbreviations: T = Tertiary, E = Eocene, Ø = Oligocene, M = Miocene, ac = angular conglomerate facies, bbc = basal breccia conglomerate unit, cg = conglomerate member, fg = fanglomerate unit, gr = gritstone member or facies, md = mudstone facies, mv = Mission Valley Formation, o = Otay Member or Formation, rb = Rosarito Beach Formation, ss-md = sandstone-mudstone member sw = Sweetwater Member or Formation.

and Las Glorias members), and sedimentary breccias (Mira al Mar Member). Importantly, no bentonites have been reported in direct association with basalts of the Rosarito Beach Formation. Deméré et al. (1984) summarized the radiometric and paleontologic evidence for the middle Miocene age (14-16 Ma) of the Rosarito Beach Formation.

Kennedy and Tan (1977) mapped the National City, Imperial Beach, and Otay Mesa quadrangles of southwestern San Diego County. From these maps and our own field data it is evident that Kennedy and Tan assigned exposures of the "red mudstone unit" in their study area to the Mission Valley Formation. However, Kennedy and Tan did not mention the red mudstone lithology in their description of the Mission Valley, nor did they use the term "Sweetwater Formation." Kennedy and Tan mapped "unnamed fanglomerate deposits" in upper Otay Valley and around Lower Otay Reservoir "...that interfinger in part with strata of the Otay Formation to the west." As judged by their mapping of the Otay Mesa quadrangle, Kennedy and Tan's concept of the Otay Formation apparently consisted of what is here called the "gritstone" and "sandstone-mudstone" members, although they do not mention the gritstone lithology in their description of the Otay Formation. Kennedy and Tan correlated the Otay Formation with the Miocene Las Glorias Member of the Rosarito Beach Formation. However, this correlation was based solely on lithological similarity, and not on any fossil or radiometric evidence.

Kuper and Gastil (1977) recognized that much of what Artim and Pinckney (1973) had mapped as Sweetwater Formation was actually assignable to the Mission Valley Formation of Kennedy and Moore (1971). In support of this observation, Kuper and Gastil emphasized that the Mission Valley Formation contains common "Poway" rhyolite cobbles (see Kies and Abbott, 1983) that are characteristic of Eocene sedimentary rocks of southwestern San Diego County, whereas the various Sweetwater and Otay units lack Poway cobbles. Evidently then, the strata assigned by Artim and Pinckney (1973) to their "lower gritty sandstone member" of the "Sweetwater Formation" were simply the southernmost outcrops of the Mission Valley Formation.

Kuper and Gastil (1977) assigned both the "conglomerate" (their "angular conglomerate facies") and "gritstone" members to the Sweetwater (as well as the "red mudstone unit"), and restricted the term "Otay" only to the uppermost "sandstone-mudstone member." Based partly on the work of Scheidemann (1977), Kuper and Gastil proposed that the Sweetwater and Otay both be recognized as members of the Rosarito Beach Formation, and assigned both of them a Miocene age.

Scheidemann and Kuper (1979) adopted Kuper and Gastil's (1977) concept of the "Sweetwater" and suggested that this unit be re-elevated to formational status. However, they also proposed that the name "Otay" be abandoned in favor of the name "Rosarito Beach Formation." Scheidemann and Kuper (1979, Fig. 4) were the first workers to measure and describe a formal type section for the Sweetwater Formation. This section consists largely of what we refer to here as the "red mudstone unit", while the uppermost 9 m consists of gritstones here referred to the Otay Formation.

Deméré (1988) reported the first identifiable fossils from the "sandstone-mudstone member" (Otay Formation of his usage) and summarized the nomenclatural morass surrounding this unit. The diverse vertebrate assemblage studied by Deméré was collected from the EastLake development in Chula Vista during grading operations, and included fossil mammals representative of the early portion of the Arikareean North

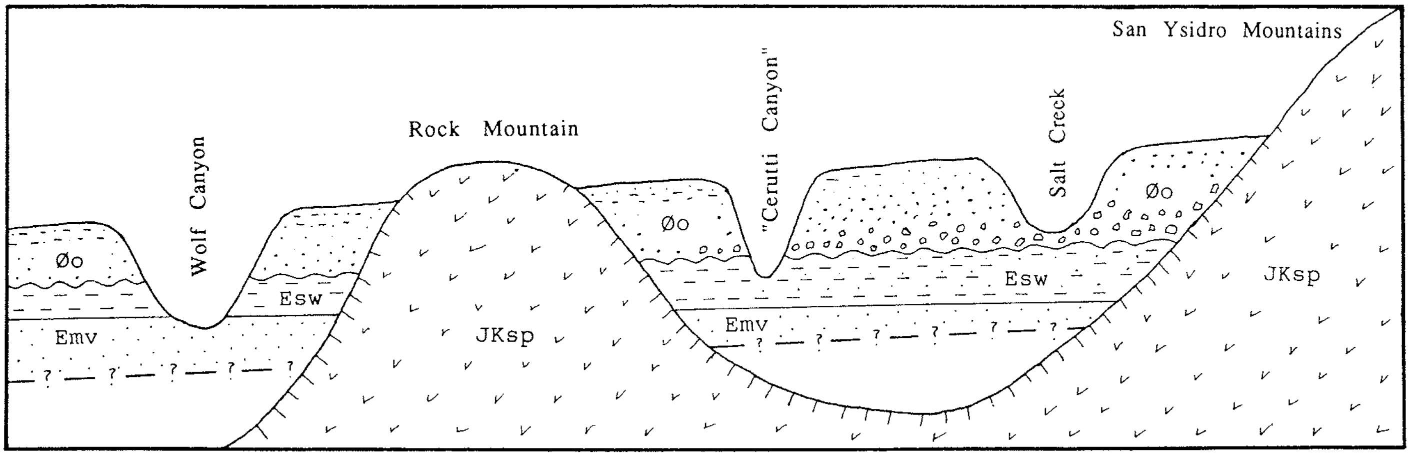

Figure 3. Generalized east-west cross-section along the north side of Otay Valley, from Wolf Canyon to the western base of the San Ysidro Mountains, showing superpositional relationships of the various lithostratigraphic uni discussed in the text. Abbreviations: JKsp = Santiago Peak Volcanics, Emv = Mission Valley Formation, Esw = Sweetwater Formation, Øo = Otay Formation. Not to scale.

American Land Mammal Age (NALMA), late Oligocene, approximately 26-28 Ma. With an Oligocene age for the Otay Formation ("sandstone-mudstone member") and a middle Miocene age (approximately 14-15 Ma; Deméré et al., 1984) for the Rosarito Beach Formation, Deméré (1988) proposed that the Otay was indeed a separate lithostratigraphic unit, distinct from the younger Rosarito Beach Formation. He suggested that the volcaniclastic nature of both formations was largely responsible for the previous miscorrelations.

SUPERPOSITIONAL AND CONTACT RELATIONSHIPS OF THE SWEETWATER AND OTAY LITHOSTRATIGRAPHIC UNITS

Some of the controversy over the age and stratigraphy of the Sweetwater and Otay seems attributable to the fact that certain basic superpositional relationships of the "red mudstone unit" and the "conglomerate" and "gritstone" members of the Otay Formation have not been well documented. In our view, Artim and Pinckney (1973) correctly implied that the "conglomerate" and "gritstone" members (together, apparently, comprising the "basal breccia conglomerate unit" of their Otay Formation) both occupied a stratigraphic position above the "red mudstone unit." In contrast, Minch et al. (1984) stated that the "red mudstone unit" occurred above the "conglomerate member", but cited no outcrops where this relationship could be seen.

Our observations over the past few years lead us to propose the following superpositional relationships (Fig. 3). First, whenever the "conglomerate" or "gritstone" members are seen in contact with the "red mudstone unit", the former units always overlie the latter, and the contact is erosional. Second, the "gritstone member" gradationally overlies the "conglomerate member" wherever the two are seen in contact. Finally, the "sandstone-mudstone member" always overlies the "gritstone member." In some outcrops, this contact is distinct, with up to 1 m of erosional relief (Deméré, 1988). In other outcrops, however, the contact is gradational (Kuper and Gastil, 1977). Critical outcrops showing these relationships are:

(1) "Cerutti Canyon" (informal name)- the second small south-draining canyon east of the eastern base of Rock Mountain, on the north side of Otay Valley (lat. 32°35'39"N., long. 116°58'16"W.): Boulder conglomerate containing distinctive coarse-grained granodioritic clasts and metavolcanic clasts disconformably overlies a 7 m (exposed) thickness of heavily bioturbated, grayish red (10 R 4/2) and pale greenish yellow (10 Y 8/2)-mottled, slightly sandy massive mudstone. Relief on the contact is at least 10 cm. The conglomerate is in turn gradationally overlain by the "gritstone member", which is in turn gradationally overlain by the "sandstone-mudstone member" (Measured Section 1, Figs. 4 and 5).

(2) "Mile 5 Cut" (informal name)- roadcut on east side of Otay Lakes Road, east of the north arm of Lower Otay Reservoir (lat. 32°38'12"N., long. 116°55'17"W.): 3.3 m of mottled, grayish red and pale greenish yellow, sandy mudstone containing rare, unidentifiable fossil bone fragments is erosionally overlain by at least 3.3 m of coarse gritstone containing common angular plutonic and metavolcanic cobbles. Relief on the contact is about 1.5 m.

LITHOSTRATIGRAPHIC UNITS OF THE SWEETWATER AND OTAY FORMATIONS, LITHOLOGY AND AREAL DISTRIBUTION

Sweetwater Formation ("red mudstone unit")

Lithology. As discussed herein, the Sweetwater Formation is redefined to include only the "red mudstone unit", which is equivalent to the "upper red claystone member" of Artim and Pinckney's (1973) "Sweetwater Formation." The Sweetwater is composed of numerous stacked, fining-upward sedimentation units. The basal part of each sedimentation unit is composed of very light gray to light greenish gray (5 G 8/1), friable, coarse-grained arkosic sandstone and pebbly gritstone. Clasts in these pebbly gritstones have not been studied in detail, but are generally subangular to subrounded and are composed of a variety of metavolcanic and granitic lithotypes. The metavolcanic clasts were presumably derived from the Santiago Peak Volcanics basement rocks currently exposed in the San Miguel, Jamul, and San Ysidro Mountains to the east. The granitic clasts were presumably derived from Cretaceous plutons of the Peninsular Ranges, currently exposed to the east of the mountains named above. We have not seen any Poway rhyolite clasts in the Sweetwater Formation. The gritstone in the basal part of these sedimentation units is dominated by subangular to subrounded granules of quartz, feldspar, and plutonic rock fragments, with a lesser amount of metavolcanic rock fragments. These basal pebbly gritstones grade upward into light brown (5 YR 6/4) and light greenish gray, friable, coarse- to fine-grained sandstones, which in turn grade upward into light brown blocky siltstones and moderate pink (5 R 7/4), pale red, and moderate reddish brown (10 R 4/6) sandy mudstones, often with pale greenish yellow-mottling. These reddish mudstones and siltstones comprise upwards of 50% of the stratigraphic thickness of the Sweetwater Formation.

Six stacked, fining-upward sedimentation units were observed in the Sweetwater Formation during grading at the Bonita Long Canyon Unit 7 housing development (Measured Section 2, Fig. 6). The thickness of individual sedimentation units varied from 2 to 7 m. As judged from outcrops of the Sweetwater Formation along Otay Valley Road and at the mouth of Wolf Canyon (Fig. 1), the thickness and abundance of the basal coarse-grained part of these sedimentation units decreases to the west. We have not been able to recognize a distinct lithostratigraphic unit that would correspond to the "sandstone facies" of Kuper and Gastil's (1977) "Sweetwater Formation."

Finally, it is worth noting that well-developed caliche beds appear to be absent from the Sweetwater Formation, in contrast to their common occurrence in the nonmarine portions of the Mission Valley and Friars formations in the greater San Diego area (Peterson and Abbott, 1979).

Contacts. The lower contact of the Sweetwater Formation is nonconformable where it overlies the crystalline basement (e.g., southwest flank of Dictionary Hill; Kuper, 1977). In all other areas where the lower contact has been seen, the Sweetwater Formation overlies the Mission Valley Formation. Good exposures of the Mission Valley-Sweetwater contact occur in cuts along Otay Valley Road (Kuper, 1977) and the South Bay Parkway (Scheidemann and Kuper, 1979, Fig. 3). The upper contact of the Sweetwater Formation is an erosional disconformity with the overlying Otay Formation. Locally, the relief on this contact is up to 1.5 m.

Distribution. The Sweetwater Formation is exposed from Casa de Oro in the north (e.g., SDSNH Loc. 3543, lat. 32°44'43"N, long. 116°58'25"W) to the north side of Otay Valley in the south (e.g., roadcuts on the north side of Otay Valley Road; Kuper, 1977). Additional outcrops of the Sweetwater Formation probably exist south of the International Border (Scheidemann, 1977, p. 18-19; Voorhees, 1975, p. 5). The westernmost known outcrops of the Sweetwater Formation occur immediately east of major strands of the La Nacion fault in the Encanto area (e.g., Kuper, 1977). The easternmost known outcrop is in a roadcut ("Mile 5 Cut") on the east side of Otay Lakes Road, just east of the northern arm of Lower Otay Reservoir.

Thickness. The Sweetwater Formation apparently decreases in thickness to the west, as exemplified by the outcrops of this unit in "Cerutti Canyon" and at the mouth of Wolf Canyon where the Sweetwater is only about 20 m thick. Towards the northeast at Bonita Long Canyon, the Sweetwater Formation is about 40 m thick. Artim and Pinckney (1973) and Kuper and Gastil (1977) indicated a maximum thickness for the "red mudstone unit" of 35 m and 30 m, respectively.

Otay Formation ("conglomerate member")

Lithology. As discussed herein, the "conglomerate member" is equivalent in part to the "basal breccia conglomerate" of Artim and Pinckney (1973), and equivalent to the "angular conglomerate facies" of Kuper and

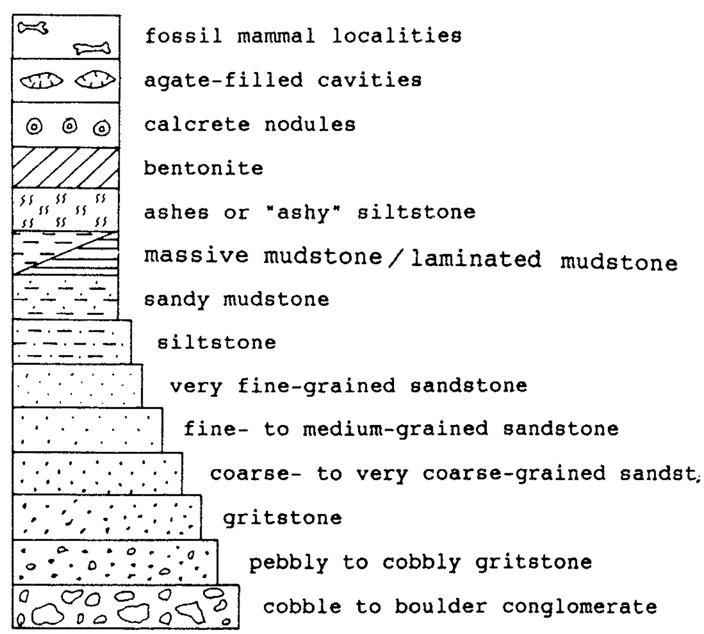

Figure 4. Key to lithologic symbols used in Measured Sections 1-5.

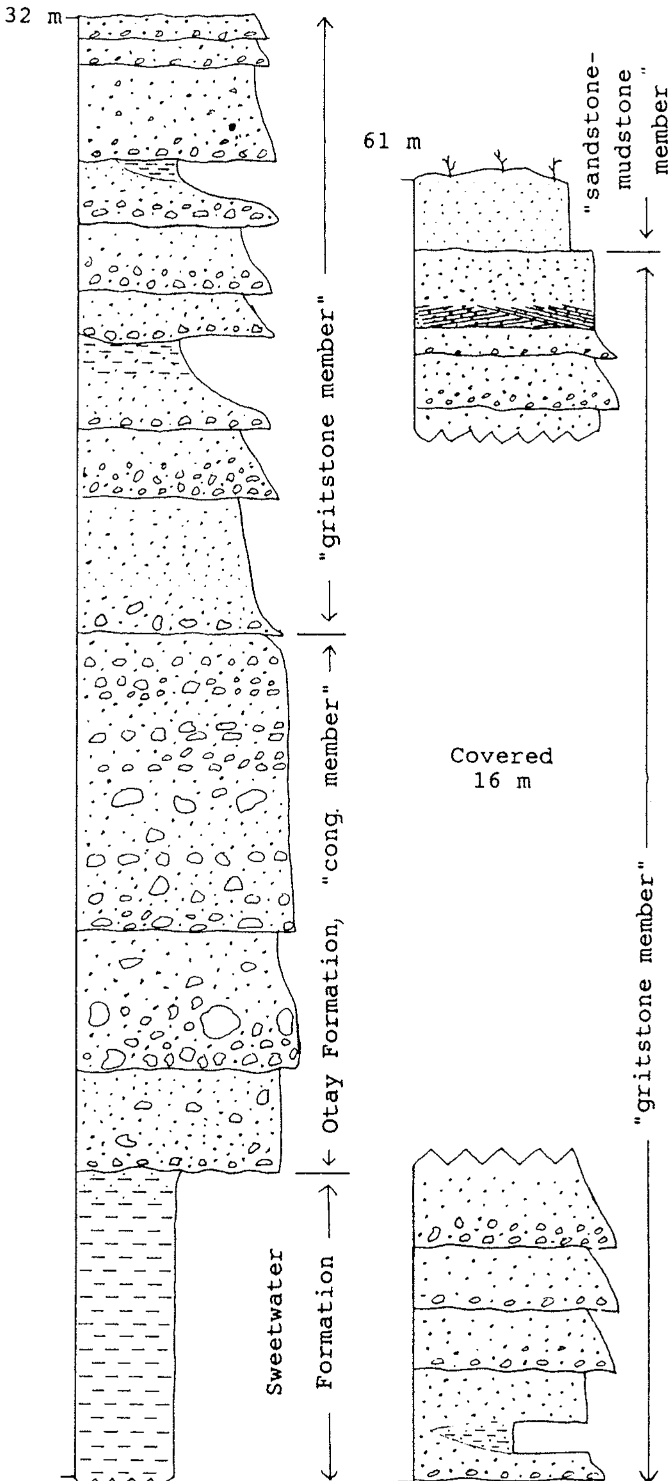

Figure 5. Measured Section 1, "Cerutti Canyon." Section measured in the second south-draining canyon east of Rock Mountain (see Fig. 1).

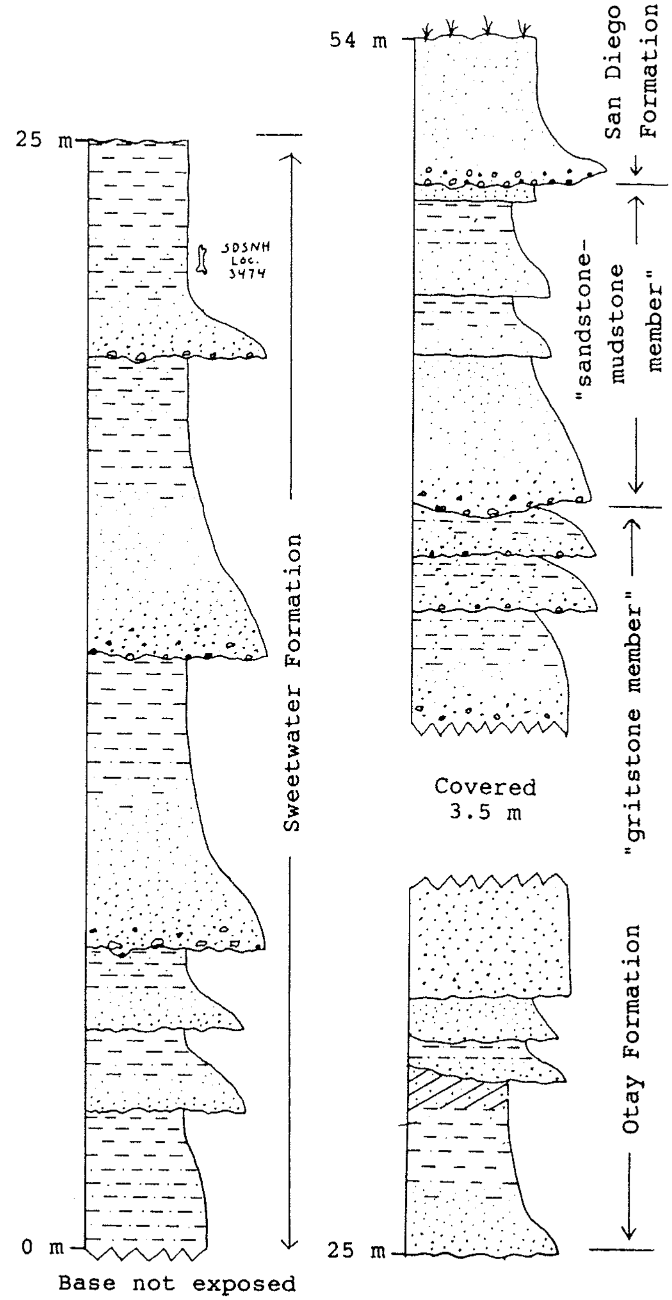

Figure 6. Measured Section 2, Bonita Long Canyon. Composite section measured in the first northwest-draining canyon north of Long Canyon (see Fig. 1).

Gastil (1977) and the "unnamed fanglomerate" of Kennedy and Tan (1977). Certain outcrops of this unit in the Proctor Valley and Otay Reservoir areas were mapped by Strand (1962) as "Pliocene-Pleistocene nonmarine sedimentary deposits." The "conglomerate member" is composed of friable cobble to boulder breccia and conglomerate. Clast types have not been studied in detail, but are generally subangular to subrounded and dominated by a variety of metavolcanic and granitic lithotypes. The metavolcanic clasts range up to 1 m in diameter and include black, gray, green, and purplish andesitic and dacitic porphyries, tuffs, and breccias, probably derived from the Santiago Peak Volcanics. Subrounded to rounded clasts of a distinctive, coarse-grained, light colored

Figure 7. Large granodioritic clast in "conglomerate member" of the Otay Formation, exposed in quarry on the south side of Otay Lakes Road, east of Lower Otay Reservoir.

granodiorite are common, ranging up to 60 cm in diameter (Fig. 7). These clasts are very similar in hand sample to granitic bedrock cropping out in roadcuts along Kimball Grade on Lyons Valley Road, about 4 km east-northeast of Jamul (NW¼ Sec. 1, T17S, R1E; Fig. 1).

Matrix of the conglomerate consists of light greenish gray and grayish yellow (5 Y 8/4) gritstone, very similar in texture to the overlying "gritstone member." This gritstone matrix is composed mainly of quartz, feldspar, and silicic plutonic fragments. Thin beds of reddish muddy sandstone occur in the lower part of the conglomerate in "Cerutti Canyon", probably reworked from the immediately underlying red mudstone of the Sweetwater Formation.

Contacts. The lower contact of the "conglomerate member" is either a nonconformity (e.g., buttress unconformity) where the unit overlies the crystalline basement (e.g., in the Otay Reservoir area; Kennedy and Tan, 1977) or an erosional disconformity where it overlies the Sweetwater Formation (e.g., in "Cerutti Canyon", Measured Section 1). The upper contact is gradational with overlying deposits of the "gritstone member."

Distribution. The "conglomerate member" crops out mainly in the Proctor Valley, Salt Creek, and Otay Reservoir areas. The westernmost known outcrop of this unit is in "Cerutti Canyon", just east of Rock Mountain. The easternmost outcrop confidently assignable to this unit is in a quarry on the south side of Otay Lakes Road (NW¼, Sec. 3, T18S, R1E), 1 km east of the gaging station on Jamul Creek. Additional deposits in the Jamul Ranch area that were mapped by Strand (1962) as "Quaternary nonmarine terrace deposits" are probably also referable to this unit. The "conglomerate member" is probably also present south of the International Border (Voorhees, 1975).

Thickness. The "conglomerate member" is only about 12 m thick at its westernmost known outcrop in "Cerutti Canyon" (Measured Section 1), but approaches 50 m in the Salt Creek area (Kennedy and Tan, 1977).

Otay Formation ("gritstone member")

Lithology. As discussed herein, the "gritstone member" of the Otay Formation is equivalent to the "gritstone facies" of Kuper and Gastil (1977; excluding the gritstone beds that they recognized within the "red mudstone unit"). The "gritstone member" is grossly similar to the "red mudstone unit" of the Sweetwater Formation in that it is also composed of several stacked, fining-upward sedimentary sequences. It differs significantly from the Sweetwater Formation in that only rarely does it contain any significant beds of terrigenous siltstone or mudstone, and when present these beds lack the distinctive pale red to moderate pink colors of the Sweetwater. Sedimentation units within the "gritstone member" are generally laterally continuous and tabular in geometry, rather than channelized. The basal part of each fining-upward sequence is composed of very light gray to grayish orange (10 YR 7/4), friable to well-cemented, coarse to very coarse, pebbly gritstone. Clast types in this unit are similar to those found in the underlying "conglomerate member." In outcrops adjacent to topographic highs of basement rocks of the Santiago Peak Volcanics, the gritstone is locally dominated by angular to subangular metavolcanic clasts (Measured Section 3). In general, the "gritstone member" is composed of subangular to subrounded granules of quartz, feldspar, and plutonic rock fragments, with lesser amounts of metavolcanic fragments. When complete, the coarse basal part of each sedimentation unit grades upward into grayish orange, gritty, coarse- to fine-grained, silty sandstones that occasionally contain fossil vertebrates. Rare beds of bluish gray (5 B 7/1) bentonite occur in the "gritstone member" (e.g., Measured Section 2, outcrop now destroyed). Opal-bearing horizons up to 1 m thick occur in the "gritstone member" in the Bonita Long Canyon and Salt Creek areas.

Contacts. The "gritstone member" gradationally overlies the "conglomerate member" wherever the two are seen in contact (e.g., Measured Section 1). Where the "conglomerate member" is absent, the "gritstone member" disconformably overlies the Sweetwater Formation (e.g., "Mile 5 Cut"), generally with up to 1 m of erosional relief.

The "gritstone member" is overlain by the "sandstone-mudstone member." This contact can either be gradational (e.g., along the aqueduct access road north of Otay Valley, between Rock Mountain and Lower Otay Reservoir) or erosional (e.g., Measured Section 2).

Distribution. The "gritstone member" crops out from Encanto in the north and west, south to the south side of Otay Valley, and east to the Otay Reservoir area (Kuper and Gastil, 1977). The "gritstone member" probably also occurs south of the International Border (Voorhees, 1975).

An erosional remnant of sedimentary rock was mapped in the Casa de Oro and Dictionary Hill areas by Strand (1962), and classified as "Pliocene-Pleistocene nonmarine sedimentary deposits." A west-facing cut behind 9594 Lamar Street (elevation about 750') exposes about 7 m of grayish yellow (5 Y 8/4), pebbly gritstones and muddy, coarse-grained sandstones. It seems probable that the sedimentary deposits in this area are a northeastern remnant of the "gritstone member" of the Otay Formation. G. Gastil (pers. comm.) has independently come to the same conclusion.

Excellent outcrops of the "gritstone member" may be seen along Chester Grade on the south side of Otay Valley, in roadcuts along the aqueduct access road just north of Otay Valley, and in new roadcuts along both sides of Telegraph Canyon Road east of Paseo Ladera.

Thickness. The "gritstone member" was about 41 m thick at Cerutti Canyon (Measured Section 1), 16 m thick in the Bonita Long Canyon area (Measured Section 2), and 16 m thick at Salt Creek (Measured Section 3, Fig. 8).

Otay Formation ("sandstone-mudstone member")

Lithology. The "sandstone-mudstone member" is equivalent to the Otay Member of the Rosarito Beach Formation of Kuper and Gastil (1977), and the Otay Formation of Deméré (1988). Although no distinct boundary exists between them, the lower part of the "sandstone-mudstone member" is generally coarser-grained than the upper part.

The lower part of the "sandstone-mudstone member" is composed of several stacked sedimentation units. These sedimentation units generally begin with a basal, often conglomeratic, very light gray, coarse-grained, locally cross-stratified sandstone. Clasts in the basal part of these sedimentation units are angular to subrounded and are dominated by metavolcanic pebbles. These pebbly coarse-grained sandstones grade upward into white to light gray, friable, medium- to fine-grained sandstones, which may display planar, trough, and low-angle cross stratification. These finer-grained sandstones grade upward into laterally continuous beds of pale yellowish brown (10 YR 6/2), vertebrate-bearing sandy siltstone and mudstone. These siltstone and mudstone beds range up to 2 m in thickness and are in turn erosionally overlain by the next coarse-grained sandstone sequence, in places with up to 2 m of local relief. Laterally continuous beds of very light gray bentonite up to 30 cm thick are commonly present in the finer-grained parts of these sequences.

Sandstone sequences in the upper part of the "sandstone-mudstone member" are generally fine- to medium-grained, and lack the metavolcanic pebbles commonly present in the coarse-grained sandstones in the lower part of this member. The upper part of this member also contains several laterally-persistent sequences of pale reddish brown (10 R 5/4) mudstone, interbedded with pale greenish yellow (10 Y 8/2) mudstone containing ostracods, nonmarine gastropods, vertebrates, and unidentified plant material (Measured Section 4, Fig. 9). These distinctive lithologies were well exposed during grading at the EastLake Greens development, and have not been observed in the lower part of the "sandstone-mudstone-member."

Contacts. The lower contact of the "sandstone-mudstone member" is generally gradational with the underlying "gritstone member" as noted earlier by Kuper and Gastil (1977). However, locally this contact is erosional and channelized with up to 1 m of local relief (Deméré, 1988).

Distribution. The "sandstone-mudstone member" crops out from the southwest corner of Otay Mesa near the International Border to just west of Upper Otay Reservoir and north to at least the north side of Sweetwater Valley (Kuper, 1977). Additional outcrops of the "sandstone-mudstone member" probably exist south of the International Border (e.g., Scheidemann, 1977).

Good exposures of the "sandstone-mudstone member" occur along Telegraph Canyon Road between Paseo Ladera and Otay Lakes Road, along Chester Grade, and in the abandoned bentonite quarries (Cleveland, 1960) along the south side of Otay Valley. This member was well exposed during development of the EastLake Hills and Shores, EastLake Business Center, and EastLake Greens project areas in eastern Chula Vista.

Thickness. The "sandstone-mudstone member" reaches a maximum thickness of about 35 m in the EastLake Greens area (Measured Section 4).

FOSSILS AND AGE OF THE SWEETWATER FORMATION

Fossils

The first identifiable fossils from the Sweetwater Formation ("red mudstone unit") are described by Walsh (this volume). A micromammal assemblage from the lower part of the formation includes the didelphid marsupial *Peradectes* sp., the insectivore *Sespedectes* sp., the rodents *Simimys simplex*, *Microparamys* sp., and *Presbymys* sp., and an unidentified small ?cylindrodontid rodent. Only sparse, unidentified ?eomyid and myomorph rodent material has been collected from the upper part of the Sweetwater Formation.

Age

The taxa described by Walsh (this volume) indicate a probable latest Uintan and/or Duchesnean (late Eocene) age for at least the lower part of the Sweetwater

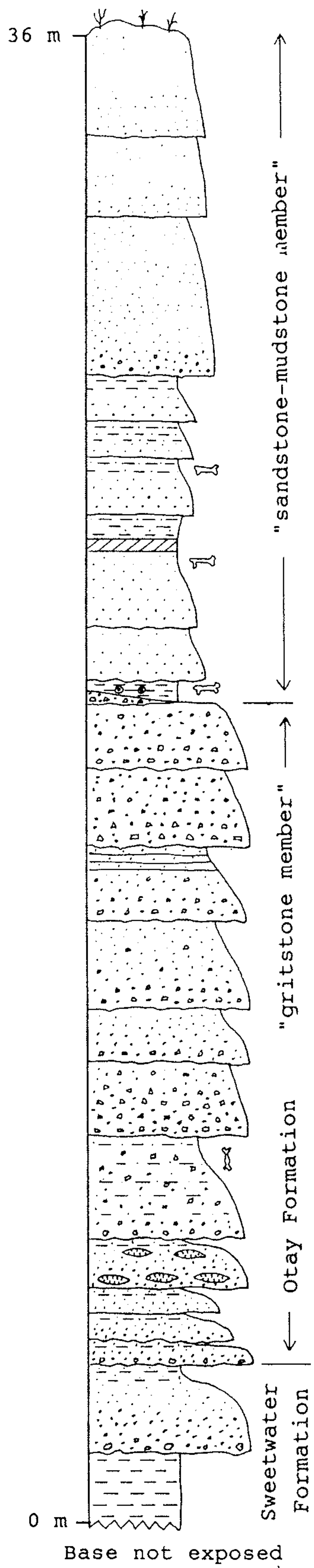

Figure 8. Measured Section 3, Salt Creek. Section measured in the Salt Creek development, Proctor Valley (see Fig. 1).

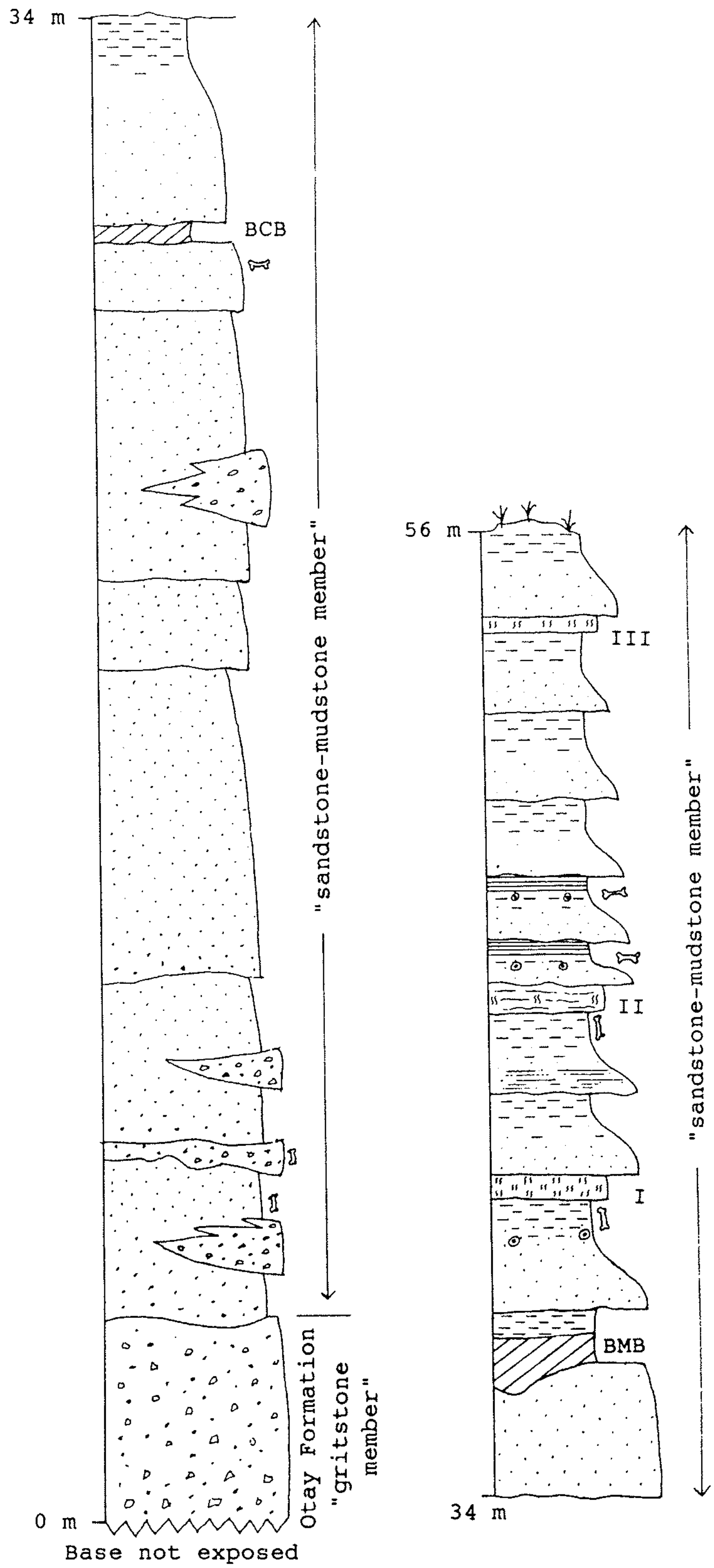

Figure 9. Measured Section 4, Eastlake Greens. Composite section measured in the Eastlake Greens development west of Lower Otay Reservoir (see Fig. 1). Possible ash beds indicated by "I", "II", and "III". BMB = "Brown Marker Bentonite"; BCB = "Business Center Bentonite."

Formation. The Duchesnean-Chadronian land mammal age boundary is placed at about 37 Ma by Prothero and Swisher (1991). This serves as a minimum age for the lower part of the Sweetwater Formation. Although it is conceivable that the uppermost part of the Sweetwater could be of Chadronian age, there is currently no evidence for it.

The Mission Valley Formation, which underlies the Sweetwater Formation, contains land mammal fossils correlative with the later portion of the Uintan NALMA (Walsh, 1987). In addition, a bentonite bed within the Mission Valley Formation has recently been dated by the single crystal Ar/Ar method at 42.18 Ma (J.D. Obradovich, in Berry, this volume); this provides a maximum age for the Sweetwater Formation. Together, this biochronologic and radiometric evidence suggests that most if not all of the Sweetwater Formation is probably between 37 and 42 Ma (late Eocene).

FOSSILS AND AGE OF THE OTAY FORMATION

Fossils

"Gritstone member". Vertebrate fossils from exposures of the "gritstone member" in the EastLake area include sparse remains of *Mesocyon*, *Hypertragulus*, and *Sespia*. These fossils have been collected from SDSNH localities 3461 and 3566 and together indicate correlation with the early portion of the Arikareean NALMA. Schultz and Falkenbach (1968) record the earliest occurrence of the leptauchenine oreodont *Sespia* at the base of the Gering Formation in Nebraska (earliest Arikareean), and Tedford et al. (1985) have utilized the first appearance of *Sespia* as a datum to define the Whitneyan/Arikareean boundary in the Great Plains.

"Sandstone-mudstone member". Vertebrate fossil remains were first reported from the Otay Formation by Deméré (1986; 1988). These fossils were all recovered from the "sandstone-mudstone member" and included well preserved remains of 18 species of terrestrial mammals. Deméré (1988) named this assemblage the EastLake local fauna after exposures of the Otay Formation at EastLake in eastern Chula Vista. The co-occurrence of the rodents *Leidymys* and *Meniscomys*, the carnivores *Mesocyon*, *Hyaenodon*, and *Nimravus*, and the artiodactyls *Hypertragulus*, *Mesoreodon*, *Sespia*, and *Miotylopus* in the EastLake local fauna indicate a correlation with the early portion of the Arikareean NALMA as defined in the Great Plains of the western interior (Tedford et al., 1985). Deméré (1988) went on to correlate the Otay Formation with the Gering Formation and Sharps Formation of the Great Plains, the Turtle Cove Member of the John Day Formation of eastern Oregon, and the lower Tecuya Formation and upper Sespe Formation of southern California. Since 1988 a number of additional localities have been collected from the "sandstone-mudstone member" in eastern Chula Vista.

Age

A bentonite bed within the "sandstone-mudstone member" has recently been dated by the single crystal Ar/Ar method at 28.86 Ma (J.D. Obradovich, in Berry, this volume). This agrees closely with a radiometric date of 28.2 ± 0.2 Ma obtained by Mason and Swisher (1989) from the Willard Canyon tuff in the upper portion of the Sespe Formation at South Mountain, Ventura County, California. This part of the Sespe Formation has produced remains of the oreodont *Sespia*, as well as other fossil land mammals correlative with the early portion of the Arikareean NALMA (Mason and Swisher, 1989). Prothero (this volume) correlates a magnetically-reversed interval in the "sandstone-mudstone member" of the Otay with Chron C10R as calibrated by Prothero and Swisher (1991), late Oligocene. Prothero goes on to suggest a close correlation between this reversed interval and that recently documented for the Gering Formation in the type area of the Arikareean NALMA.

The biochronologic correlations of the Sweetwater and Otay formations are summarized in Figure 10.

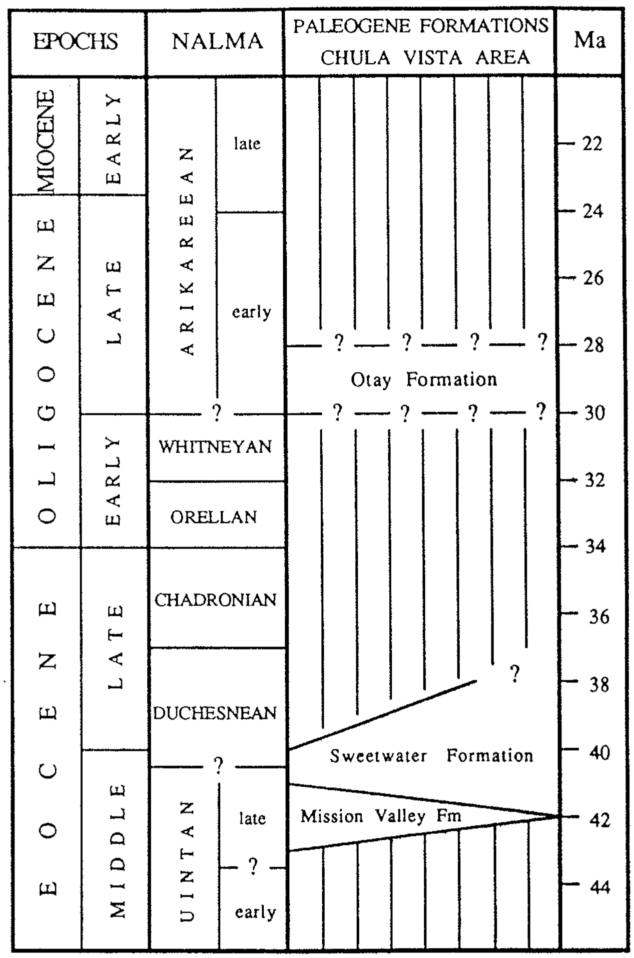

Figure 10. Age correlations for the Mission Valley, Sweetwater, and Otay formations. NALMA = North American Land Mammal "Age". Geochronometric ages of epoch and land-mammal "age" boundaries from Prothero and Swisher (1991).

ORIGIN AND DEPOSITIONAL ENVIRONMENTS OF THE SWEETWATER FORMATION

Depositional Environments

Kuper and Gastil (1977) suggested that at least part of the Sweetwater Formation (i.e., presumably the "red mudstone unit") was deposited in a playa-type environment. This would imply that deposition occurred within an enclosed basin; in this case a structural trough bounded by western and eastern topographic highs. The eastern structural high referred to by Kuper and Gastil (1977) was the Peninsular Ranges, while that to the west was an uplifted block of the Catalina Schist terrane (Stuart, 1979). It is well documented that a western high of Catalina Schist served as the source area for detritus now found in the middle Miocene Mira al Mar Member of the Rosarito Beach Formation (Minch, 1967) and the middle Miocene San Onofre Breccia (Stuart, 1979). However, we know of no evidence for the existence of this western block during the late Eocene nor the late Oligocene. Rather, uplift of the Catalina Schist terrane apparently began during the early Miocene, in response to transtensional faulting of the southern California Borderland (Ehlig, 1979). This is consistent with the lack of Catalina Schist detritus in the Sweetwater and Otay formations. In short, there is currently no evidence that the "red mudstone unit" of the Sweetwater Formation was deposited in an enclosed, playa-like basin.

The occurrence in the Sweetwater Formation of stacked, fining-upward sedimentation units suggests cyclic deposition, perhaps in a river channel and floodplain setting. The basal pebbly gritstones and sandstones may represent fluvial channel and/or sheetflood deposits. The bioturbated, oxidized, mammal-bearing mudstones of the upper portions of these sedimentation units are interpreted as paleosols that formed upon fine-grained overbank deposits. Grossly similar lithologies and inferred depositional settings have been proposed for the upper Eocene red beds of the middle member of the Sespe Formation, Ventura County (Taylor, 1983).

Nature of the Mission Valley-Sweetwater Contact

The amount of time represented by the Mission Valley-Sweetwater formational contact is not accurately known. Given the Miocene age assigned to the Sweetwater Formation by most workers, this contact was thought to be unconformable, representing a hiatus of 20-25 Ma (late Eocene to Miocene). However, based on the fossil mammals recovered from the Sweetwater, the amount of time represented by this contact need not have been very great (possibly zero, and probably no more than 5 million years; Walsh, this volume). Indeed, some preliminary stratigraphic observations suggest that this contact may be intergradational, and the unconformable relationship proposed by previous workers should be re-evaluated.

In an outcrop (SDSNH Loc.3568) located at the extreme southwestern corner of the Mount Miguel High School baseball fields in Spring Valley (Measured Section 5, Fig. 11), pale red (10 R 6/2), massive sandy mudstones similar to those of the Sweetwater Formation are overlain by a yellowish gray (5 Y 8/1), pale reddish brown-stained, well-sorted, fine-grained sandstone bed similar in lithology to the Mission Valley Formation. This bed is in turn overlain by two different sedimentation units of reddish, fine-grained muddy sandstone containing rare oyster shell fragments and common calcite steinkerns of high spired gastropods (cf. *Bittium* sp. and

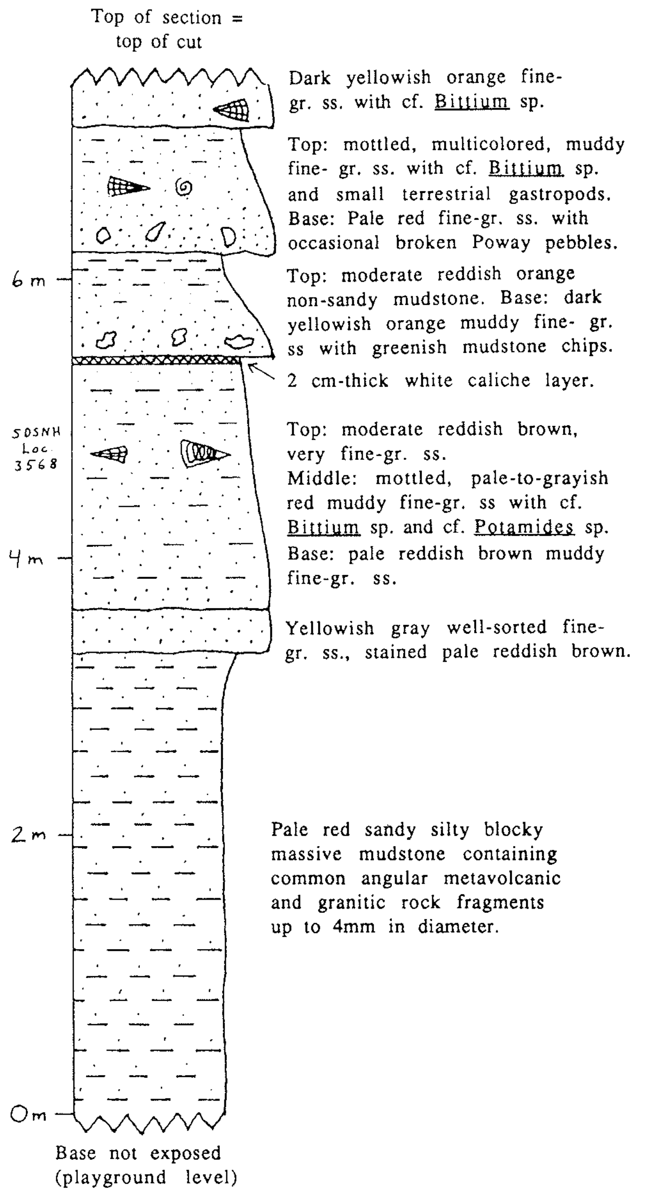

Figure 11. Measured Section 5, Mount Miguel High School. Possible intergradational contact between Mission Valley and Sweetwater formations suggested by the association of brackish-water molluscs with pale red massive mudstones. Section located at the southwesternmost corner of the Mount Miguel High School baseball fields (see Fig. 1).

cf. *Potamides* sp.), taxa that indicate brackish-water deposition. Broken Poway rhyolite pebbles occur at the base of the upper sedimentation unit. In a nearby outcrop (SDSNH Loc. 3569) located just west of Avondale Elementary School, at least 2 m of pale red, massive, "Sweetwater-like" mudstone is overlain by a poorly sorted pebbly sandstone bearing angular metavolcanic clasts, oyster shells, and abundant steinkerns of brackish water mollusks. We suggest that an intergradational contact between the Sweetwater and Mission Valley formations is the most likely explanation for these observations.

Scheidemann and Kuper (1979; Fig. 3) discuss an outcrop along the South Bay Parkway that appears to show an angular discordance between the Mission Valley and Sweetwater formations. However, it is unclear whether this discordance is tectonic in origin or perhaps a result of differences in original depositional dip. The occurrence above the alleged unconformity of well-sorted, light gray, "Mission Valley-like" sandstones (i.e., the "sandstone facies" of Kuper and Gastil's "Sweetwater Formation") could also be interpreted as evidence for an intergradational contact between these two units. Evaluation of this possibility requires further investigation.

Possible Causes for Onset of Deposition of the Sweetwater Formation

Whether it is intergradational or not, the contact between the Poway clast-bearing, largely shallow-marine, well-sorted sandstones of the Mission Valley Formation, and the Poway clast-lacking, non-marine, reddish mudstones and poorly sorted sandstones of the Sweetwater Formation implies a significant change in depositional setting. The most likely explanations for this change involve an episode of uplift and/or a lowering of sea-level. Evaluation of these two possibilities requires discussion of the Pomerado Conglomerate (Peterson and Kennedy, 1974) which also overlies the Mission Valley Formation, but crops out to the north of occurrences of the Sweetwater Formation.

The Pomerado Conglomerate is the youngest preserved lithostratigraphic unit of the Eocene Poway Group (Kennedy, 1975). The Pomerado has not yet yielded any fossils, but is assumed to be at least in part of late Eocene age on the basis of its reportedly gradational contact with the underlying Mission Valley Formation (Peterson and Kennedy, 1974). Like the Sweetwater/Mission Valley contact, the Pomerado/Mission Valley contact also represents a regressive episode (Peterson and Kennedy, 1974). However, the relative age of the Pomerado and Sweetwater formations is unclear, as the two formations have not been seen in contact. The fact that the Sweetwater Formation lacks Poway rhyolite clasts can be explained in two different ways: (1) it lacks Poway clasts because deposition began after cessation of the delivery of these clasts to the "Poway Fan" (see Howell and Link, 1979) -- if so, then the Sweetwater Formation is entirely younger than the Pomerado Conglomerate; (2) it lacks Poway clasts because it accumulated in a basin that was depositionally isolated from the Poway Fan (e.g., by the bedrock hills in the La Mesa and Spring Valley areas; see maps of Kuper, 1977; Kennedy, 1975) -- if so, then the Sweetwater Formation could be contemporaneous with the Pomerado Conglomerate.

Unfortunately, timing of the cessation of deposition on the Poway Fan is not currently precise enough to allow a clear choice between these two alternatives. Kies and Abbott (1983) proposed that the transport of exotic rhyolitic material to the Pacific coast was disrupted in the late Eocene or early Oligocene. This disruption was attributed to the development of an extensional tectonic regime between the Pacific coast and the presumed rhyolitic source areas in Sonora, Mexico (Dickinson, 1982; Abbott and Smith, 1989). Conceivably, this new tectonic regime could have been responsible for an uplift of the Peninsular Ranges, thereby bringing about the onset of Sweetwater deposition. Such an uplift cannot be ruled out as a cause for the onset of deposition of the Sweetwater, and this hypothesis should be subjected to further testing.

Alternatively, the onset of deposition of both the Pomerado and Sweetwater formations could be explained by a global drop in sea-level that took place after the marine transgression represented by the Mission Valley Formation. Haq et al. (1987) identify two major global sea-level minima in the late Eocene. These are estimated by them as occurring at about 42.0 Ma and 39.5 Ma. The 42.0 Ma event is disconcertingly close to the 42.18 Ma age of the bentonite from the Mission Valley Formation, which presumably corresponds closely to the maximum marine transgression represented by this formation. This discrepancy cannot be explained at this time. Alternatively, the contact between the Mission Valley Formation and the Sweetwater and/or Pomerado formations may correspond to the 39.5 Ma global sea-level drop recognized by Haq et al. (1987). Confident identification of which if any of these events corresponds to the Mission Valley-Pomerado and/or Mission Valley-Sweetwater contacts must await additional evidence.

ORIGIN AND DEPOSITIONAL ENVIRONMENTS OF THE OTAY FORMATION

Depositional Environments

A detailed sedimentological study of the rocks of the Otay Formation is beyond the scope of the present report. As previously mentioned, however, the "conglomerate", "gritstone", and "sandstone-mudstone" members of the Otay Formation appear to us to compose different parts of a single evolving alluvial fan/fluvial depositional system, and we offer the following as preliminary evidence in support of this view.

"Conglomerate Member". Kuper and Gastil (1977) and Scheidemann and Kuper (1979) suggested that rocks here assigned to the "conglomerate member" accumulated as lag deposits in a "fan head" setting. Kennedy and Tan's (1977) use of the term "fanglomerate" to describe the same deposits also implies an alluvial fan setting.

Based on the outcrop distribution of the "conglomerate member" along Jamul and Proctor Valley creeks, we suggest that these boulder conglomerates represent the trunk channels of the Oligocene precursors of these creeks. As evidence for this, we note that east of Lower Otay Reservoir, these deposits are in part confined to a narrow gorge carved into metavolcanic basement rocks. Further east near the Jamul Ranch, probable correlatives of these conglomerates occur as perched channel remnants, similar to those known from the Eocene Ballena channel near Fernbrook (Howell and Link, 1979). Judging from the modern topography in the Jamul Valley area, it appears that the mouth of the Oligocene "Jamul River" gorge was located in the Lower Otay Reservoir area. Accordingly, deposits of the "conglomerate member" to the west of Lower Otay Reservoir may represent deposition near the apex of an Oligocene alluvial fan, where the ancestral Jamul Creek escaped the confinement of the metavolcanic gorge and dumped its sediment load onto the "Otay Fan" (informal name). Again, the sedimentology of these deposits requires further study.

"Gritstone Member". Kuper and Gastil (1977) and Scheidemann and Kuper (1979) proposed that the sediments equivalent to our "gritstone member" were deposited under sheetflood conditions. They also noted that this unit displays "...crude cross-bedding and local channeling, suggestive of braided stream activity." We concur. The consistently graded and tabular nature of these sedimentation units suggests cyclic depositional events such as sheetflood deposits in braided streams or on the more distal portions of alluvial fans (Bull, 1972).

"Sandstone-mudstone Member". Scheidemann and Kuper (1979, p. 107; Fig. 10) proposed that rocks here assigned to the "sandstone-mudstone member" were "...deposited on a northeasterly dipping alluvial plain via ephemeral braided streams, sheetfloods and debris-flows."

The angular pebble conglomerates in the "sandstone-mudstone member" occur along basal erosional surfaces and may represent channel lag deposits. Sandstone beds displaying parallel and low-angle cross stratification are similar to deposits considered by Taylor (1983) to represent longitudinal bar deposits in a sandy, braided stream setting. The structureless sandstones comprising the bulk of the "sandstone-mudstone member" may represent both channel and bar deposits of a braided stream. These sandstones commonly form the basal portion of stacked, fining-upward sequences that are capped by massive, laterally continuous, vertebrate fossil-bearing siltstones and mudstones. These siltstones and mudstones appear to represent overbank deposition in a floodplain setting. Calcrete nodules are commonly present in these fine-grained beds and suggest soil formation on the floodplain in areas isolated from the active channels.

The laterally continuous, interbedded siltstones and mudstones near the top of the "sandstone-mudstone member" contain ostracods, nonmarine mollusks, and reed-like plant remains suggestive of quiet water (e.g., lacustrine) deposition.

Although the sandstones of the Miocene Rosarito Beach Formation may have been derived from the southwest, Scheidemann and Kuper's (1979) suggestion of a southwestern source for the strata here assigned to the "sandstone-mudstone member" of the Otay Formation is not supported by our observations. The metavolcanic and granitic pebbles commonly found at the base of sandstone channels in the "sandstone-mudstone member" are lithologically indistinguishable from those found in the underlying "conglomerate" and "gritstone" members, and are consistent with an eastern Peninsular Ranges source. We have not seen any clastic material in any of the three members of the Otay Formation likely to have been derived from a western source (e.g., Catalina Schist or Rosarito Beach Formation basalt).

Possible Causes for Onset of Deposition of the Otay Formation

The presence of a coarse, nonmarine conglomerate at the base of the Otay Formation in disconformable contact with the underlying Sweetwater Formation implies that its deposition began in response to an increase in stream competence brought about by one or more causal geological events, such as: (1) a significant increase in rainfall in the later Oligocene; (2) a later Oligocene episode of uplift of the Peninsular Ranges and/or (3) a later Oligocene global sea-level drop.

An increase in rainfall seems unlikely, because the "conglomerate" and "gritstone" members are extremely immature in texture and composition, and contain little of the argillaceous material that would be expected as a result of increased chemical weathering.

Mid-Tertiary uplift of the Peninsular Ranges is a possible cause for the onset of deposition of the late Oligocene (ca. 29 Ma) Otay Formation, but the earliest evidence for this uplift in the southern California area is early Miocene (Gastil et al., 1975).

Finally, a global sea-level drop may have increased the competence of the late Oligocene drainages, thereby initiating deposition of the basal "conglomerate member" of the Otay Formation. According to Haq et al. (1987), the largest relative global sea-level drop in the Tertiary took place at 30 Ma. These authors estimate the magnitude of this relatively sudden change in sea-level to

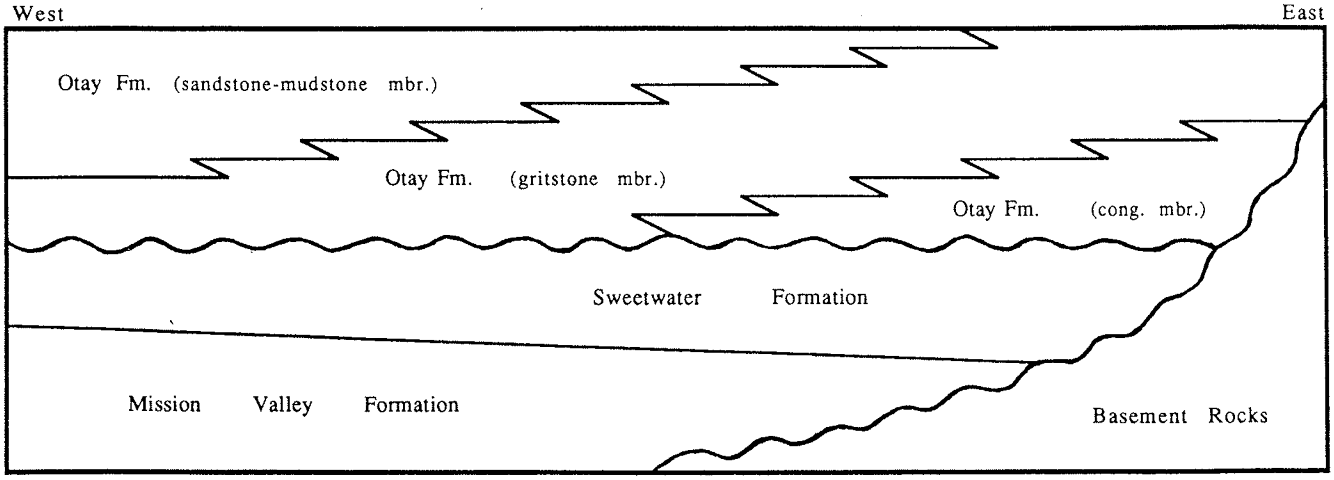

Figure 12. Proposed stratigraphic relationships of the Mission Valley, Sweetwater, and Otay formations in southwestern San Diego County.

be about 150 meters. If the timing of this event and the 28.86 Ma date on the bentonite in the Otay Formation are accurate, then this sea-level drop occurred about 1.1 Ma before the deposition of the upper, "sandstone-mudstone member" of the Otay Formation. Given the coarse and immature nature of the "conglomerate" and "gritstone" members of the Otay, it is conceivable that both of these units could have been deposited in less than one million years. This would be consistent with the fact that the oreodont genus *Sespia* is found to occur throughout the "gritstone" and "sandstone-mudstone" members of the Otay, yet is reported to have a very short stratigraphic range in the classic upper Oligocene sedimentary sequence of the Great Plains (Schultz and Falkenbach, 1963; Tedford et al., 1985). Thus, the global sea-level drop at 30 Ma is a possible causal event for the onset of deposition of the Otay Formation. The recovery in global sea-level identified by Haq et al. (1987) as occurring from 30 Ma to 28.5 Ma would also be consistent with the overall fining-upward trend of the Otay Formation as a whole.

If a late Oligocene global sea-level fall is responsible for initiation of deposition of the Otay Formation, then similar "Otay-like" depositional events should be recognizable elsewhere along the Pacific coast. Howard (1989) recognized a major unconformity in the nonmarine portion of the upper Sespe Formation in the Santa Ynez Mountains and suggested that this unconformity coincided with the late Oligocene change in sea-level discussed above. Mason and Swisher (1989) further suggested that this unconformity was responsible for the lack of latest Eocene through mid-Oligocene (Chadronian-Whitneyan) vertebrate fossils in the upper portion of the Sespe Formation. They noted that early Arikareean mammals, including the oreodont *Sespia*, occur above the unconformity recognized by Howard (1989), whereas late Eocene mammals occur immediately below this unconformity. These interpretations are consistent with our recognition of a similar hiatus between the Sweetwater and Otay formations in San Diego County.

Proposed Depositional Model for the Otay Formation

Our stratigraphic and depositional model for the Otay Formation is illustrated schematically in Figure 12. To summarize, the formation consists of a lower "conglomerate member", which grades upward and westward into the "gritstone member", which in turn grades upward and westward into the upper, "sandstone-mudstone member." The clear fining-upward and fining-westward trend within this formation reflects relatively rapid initial deposition from the east, followed by a gradual change to more distal fluvial environments.

CONTRASTING TECTONIC SETTINGS OF THE OTAY AND ROSARITO BEACH FORMATIONS

We have already discussed the lithologic, radiometric, and paleontologic evidence for separating the Otay and Rosarito Beach formations. Additional evidence is provided by the apparent differences in the tectonic settings of the two formations. At the core of this discussion is the occurrence of silicic bentonites in the Otay Formation and basaltic flow rocks in the Rosarito Beach Formation. As briefly mentioned by Deméré (1988) and discussed more fully by Berry (1986; this volume), the Otay bentonites probably represent subduction-generated volcanism in contrast to the rift-generated volcanics of the Rosarito Beach Formation. This relationship suggests that plate subduction was still active along this portion of the Pacific Coast in late Oligocene time and that initiation of rift tectonics in this area began sometime in the Miocene, prior to or coincident with accumulation of the basalts of the Rosarito Beach Formation.

CONCLUSIONS

Based on new fossil and stratigraphic evidence, the Sweetwater and Otay formations of southwestern San Diego County are redefined. The Sweetwater Formation is restricted to the distinctive "red mudstone unit", that contains mammals of late Eocene (latest Uintan and/or Duchesnean) age, ca. 42-37 Ma. Contrary to previous interpretations, the contact between the Sweetwater Formation and the underlying Mission Valley Formation appears to be gradational in some areas, and requires further study.

The Otay Formation is composed of three lithostratigraphic units that we regard as informal members. From stratigraphically lowest to highest, these are the "conglomerate", "gritstone", and "sandstone-mudstone" members. The uppermost two members of the Otay Formation have yielded early Arikareean mammals, and a bentonite in the "sandstone-mudstone member" has been dated at 28.86 Ma (Berry, this volume). Deposition of the Otay Formation may have begun in response to the large drop in global sea-level recognized by Haq et al. (1987) at 30 Ma.

Terrigenous sediments of the Sweetwater and Otay formations were both derived from the Peninsular Ranges to the east. The age and lithological evidence discussed herein reinforces the view (Deméré, 1988; Berry, this volume) that the Otay Formation is much older and formed under very different tectonic conditions than the middle Miocene Rosarito Beach Formation of Baja California.

Several problems remain concerning the Sweetwater and Otay formations. One of these is identification of the source area for the bentonites in the Otay Formation; possible candidates include the dacitic volcanic stocks at Cerro de la Calavera and Morro Hill in northwestern San Diego County (Larsen, 1948). Another problem deserving study is the detailed sedimentology and provenance of the Sweetwater and Otay formations. Finally, the Otay Formation almost certainly exists south of the International Border, but the contact between this unit and the Miocene Rosarito Beach formation remains to be identified.

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